Dark Photons in the Dalitz-like decay of a scalar

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**DP:** what do we know

**New Physics:** …, Dark matter/ Dark photons, … Monophotons

**Search through:** Cosmological observations or lab’s experiments

**Accelerator exp’s:** - CERN SPS

\[ e^- Z \rightarrow e^- Z \bar{\gamma} \rightarrow e^- Z e^+ e^- \]

\[ 10^{-5} < \varepsilon_{\gamma-\bar{\gamma}} < 10^{-3} \]

NA64

S. Gninenko PRD 89 (2014) 075008

- SINDRUM, PSI

\[ \pi^- p \rightarrow \pi^0 n \rightarrow \gamma \bar{\gamma} n \rightarrow \gamma e^+ e^- n \]

\[ \varepsilon_{\gamma-\bar{\gamma}} > 10^{-3} \]

S. Gninenko PRD 87 (2013) 035030

**Colliders @ high energies (LHC/…/FCC…)**

\[ \mathcal{S} \rightarrow \gamma \bar{\gamma} \rightarrow \gamma \bar{\nu}\nu, \quad \mathcal{S} = H, \ldots \]

\[ \varepsilon_{\gamma-\bar{\gamma}} < 3 \cdot 10^{-2} \]

\[ \mathcal{O}_{SM} \mathcal{O}_{IR} \sim \varepsilon q \bar{\gamma} \gamma q SB \mu M^{-1} \]


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In the absence of an explicit sector that breaks gauge invariance, the interactions of SM gauge bosons with fermions are approximately conformal down to QCD scale $\Lambda_{QCD} \sim O(1\text{GeV})$.

• Could we see something else – not in terms of SM?

• Should one expect new stuff?  
  Great!

• Scale invariant hidden world?

✓ The question of triggering gauge symmetry breaking in the SM is tied to the dynamical breaking of scale invariance.
**Hidden world**

At high enough energies \( Q \sim O(M) \) (UV, Cosmology)

the nearly conformal (matter) sector couples in the UV to the HIDDEN world through the exchange of heavy state(s), the messenger(s)

*Mediators in terms of ATLAS – CMS LHC Forum, arxiv:1507.00966*

**Stage I**

\[
\begin{bmatrix}
\text{Nearly conformal} \\
\text{conformal}
\end{bmatrix}
\overset{\text{heavy messenger(s)}}{\leftrightarrow}
\begin{bmatrix}
\text{Hidden world}
\end{bmatrix}
\]

Below \( UV \ M \):

\[
\frac{1}{M^d} O_{SM} \quad \frac{1}{M^{d_{UV}}} O_{UV}
\]

No masses allowed

All masses can be generated dynamically in **IR**.

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Conformal symmetry is spont. broken – low energy eff. theory contains a dilaton field

\[ x_\mu \to x'_\mu = e^{-\lambda} x_\mu , \quad \mathcal{S} = \bar{\sigma}, \quad \bar{\sigma}(x) \to \bar{\sigma}'(x') = \bar{\sigma}(x) + \lambda f, \quad f \geq v = 246 GeV \]

Below breaking scale the symmetry is realized non-linearly

\[ L \sim \sum_i g_i(\mu) O_i(x), \quad g_i(\mu) \to g_i(\mu \bar{\sigma}/f)(\bar{\sigma}/f)^{4-d_i} \]

Stage II (coupling of dilaton to DP sector in UV)

- In UV: \[ \frac{1}{M^{d_{UV}-2}} \left| \bar{\sigma}^2 \right| O_{UV}, \quad \bar{\sigma}(x) = \sqrt{H^+ H}(x), \quad m_\sigma^2 \sim x_\sigma f^2 \]

- in IR \quad \downarrow \quad \text{flows to couplings of } H \text{ to DP operator } O_{IR}

\[ \text{const} \frac{\Lambda^{d_{UV}-d_{IR}}}{M^{d_{UV}-2}} \left| H^2 \right| O_{IR} \quad \text{Scale invariance is almost breaking} \]
DM particle is the only DP within the reach of the LHC energy

Kinetic term $\sim \epsilon F_{\mu\nu} B^{\mu\nu} \quad SU_L(2) \times U_Y(1) \times U_B'(1) \iff \text{DP origin}$

Triangle anomaly coupling $L_{\gamma \gamma} = \epsilon g_{\gamma \gamma} F_{\mu\nu} B^{\mu\nu} S, \quad B^{\mu\nu} = \partial^\mu B^\nu - \partial^\nu B^\mu$

Basic object $S \to \gamma \gamma \to \gamma \bar{\nu}\nu, \quad S = \begin{cases} \text{higgs} \\ \text{dilaton} \end{cases}$

LO: $\sigma(pp \to S X) = \sigma^{\exp}(pp \to H X) \times \frac{\Gamma^{th}(S \to gg)}{\Gamma^{SM}(H \to gg)}$

QCD radiative corrections $gg \to \text{Higgs} \iff gg \to \text{dilaton}$

Increasing of $\sqrt{s} \implies \text{Approx. conformal invariance} \quad \frac{\partial g(\mu)}{\partial \mu} \equiv 0$

Breaking \( \sim f > v = \langle H \rangle_0 \) by $\mu \approx M_{UV} \exp[-8\pi^2/(b_0 g_0^2)]$

CA: $\partial_\mu K^\mu = \theta^\mu_\mu = \frac{\beta(g)}{2g} G^a \mu \nu a G^{\mu\nu a} + \sum m_q \left[ 1 + \gamma_m(g) \right] \bar{q} q \neq 0$

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Why LHC13 instead of LHC7?

\[ S \sim m_s \sim f \sim s^{\alpha/2} \]

Strong coupling theory.

At \( \sqrt{s} \) below \( \Lambda \), \( \beta(g_i) \neq 0 \) conformal breaking

\[ L \sim \sum g_i (\mu) O_i (x), \quad \theta^\mu = \sum g_i (\mu) (d_i - 4) O_i (x) + \sum \beta_i (g) \frac{\partial}{\partial g_i} L \]

Scale invariance exact if \( \beta(g_i) = 0, \quad d_i = 4 \)

\[ L_{\text{trace}} = \frac{\chi}{f^2} \theta^\mu (SM), \quad \theta^\mu \neq 0, \quad \theta^\mu (SM) = \theta^\mu (SM)_{\text{tree}} + \theta^\mu (SM)_{\text{anom}} \]

Collider physics importance:

\[ \theta^\mu (SM)_{\text{anom}} = -\frac{\alpha_s}{8\pi} b_0 \sum G^a_{\mu\nu} G^{\mu\nu,a} - \frac{\alpha}{8\pi} b_{EM} F_{\mu\nu} F^{\mu\nu} \]

Higgs has not such a coupling, only triangle-loop with heavy quarks

If QCD \( \in \) Conformal sector:

\[ \sum_{\text{light}} b_0 + \sum_{\text{heavy}} b_0 = 0 \quad \Rightarrow \quad b_0 = -11 + \frac{2}{3} n_{\text{light}} \]

compared to Higgs

**Important:** The sum is splitting over all colored particles in mass scale separated by dilaton mass \( m_s \)

- Dilaton serves as the conformal compensator up to \( f = \nu \).
- The \( \sigma \) contribution to \( S \rightarrow \gamma \gamma \) decays corresponds to including states lighter than \( \sigma \).

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Effect of DP sector on observable(s)

Mixing strength $\varepsilon$ is bounded by $\varepsilon < \frac{s^d}{(v^2 M^{d-2})^2}$

- Important: no dependence on $d_{UV}$, $d_{IR}$, $\Lambda$

- NP signals with DP increase with $\sqrt{s}$, $d$

Assume $\varepsilon \sim O(3\%)$, DP visible @ LHC for $M < 10^3$ TeV, $d=4$

For $S \rightarrow \gamma \gamma$: $L \sim O_{SM} O_{IR} \sim \varepsilon \bar{\psi} \gamma_\mu \psi S B^\mu M^{-1}$

Relevant energy scale $Q \sim m_q$, $q : top, ...$

Result: $\varepsilon < 3 \cdot 10^{-2}$, $q : top$, $d = 4$; $M > v$

LHC is a very good facility where the DM Physics can be tested well

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Upper limit on $\varepsilon < \frac{S^d}{\left(v^2 M^{d-2}\right)^2}$, \( LHC \) up to $\sqrt{s} = 14\, TeV$, $M = 800 - 1000\, TeV$, $d = 4$

Estimation of DP mass $m$.  \textit{Upper limit}

\[ Am\left( \bar{\gamma} \rightarrow \nu \bar{\nu} \right) = \frac{1}{2} f_{\nu}^{2} \nu \left( g_{\nu}^{V} \gamma_{\beta} + g_{A_{\nu}}^{V} \gamma_{\beta} \gamma_{5} \right) \nu \bar{\gamma}_{\beta} \]

\[ f_{\nu}^{2} = 4 \sqrt{2} Gm^{2}, \quad G \sim 10^{-5} \text{GeV}^{-2} \]

No final state interactions: (partial decay width)

\[ \Gamma\left( \bar{\gamma} \rightarrow \nu \bar{\nu} \right) = \frac{1}{3} \bar{\alpha} \cdot \varepsilon^{2} m, \]

\[ \downarrow \]

\[ \frac{Gg_{\nu}^{2}m^{2}}{\sqrt{2\pi \bar{\alpha}}}, \quad g_{\nu}^{2} = g_{A_{\nu}}^{2} = g_{\nu}^{2} = \frac{1}{4} \]

For $\varepsilon < 3 \cdot 10^{-2} \Rightarrow m < 3.3 \text{GeV}$
DP mass \( m \) in \( S \) ! " **! "##

more detailed calculation are needed

E.g., EM! F

\[
M \sim \%^2 m^5 G^2 \left( \ln \frac{\Lambda^2}{m^2}, \frac{1}{6}\right)^2
\]

DP mass: Combined calculations give

\[
\begin{array}{ccc}
m & m & 1^{1/2} \\
0 & \sqrt{3} & \frac{3}{3} \\
0 & \sqrt{3} & \frac{3}{3} \\
0 \sum_{l:e} & \Lambda^2 & \frac{1}{6} \frac{3}{3} \\
0 \sum_{l:e} & \Lambda^2 & \frac{1}{6} \frac{3}{3} \\
\end{array}
\]

4 0.83 GeV, \( \Lambda_\% \sim O(m_Z), e^+e^\& \& + ^\& \& ~\text{loops} ~\]

\[! = 7.6 \times 10^3\]

Agree with excl. region by BaBar (2015), E787+E949 (2014), as well as (g-2) (2014)

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Model (Higgs-Dilaton Abelian gauge theory).

- TPWF, $\delta'\left(p^2, M^2\right)$ singularities/ $\sigma(x)$ virtual state – dilaton

$$A_\mu - B_\mu \text{ mixing} \quad H - \bar{\sigma} \quad \text{LD}$$

$$L_\varepsilon = -\frac{1}{2} \varepsilon F_{\mu \nu} B^{\mu \nu} - \bar{\xi} \left( \partial A \right) \left( \partial B \right) + \bar{q} \left( i \hat{\partial} - m_q - g A \right) q - I^\mu \left( B_\mu - \partial_\mu \sigma \right)$$

Gauge inv. $A_\mu \rightarrow A_\mu + \partial_\mu \alpha$, $B_\mu \rightarrow B_\mu + \partial_\mu \alpha$, $\sigma \rightarrow \sigma + \alpha$, $q \rightarrow q e^{i g \alpha}$, $I_\mu \rightarrow I_\mu$, $\partial^2 \alpha(x) = 0$

$$F_{\mu \nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \quad B_{\mu \nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \quad \xi = \varepsilon \bar{\xi}$$

Sub-canonical scalar operator $\sigma(x) = f^{-1} \bar{\sigma}(x)$

( primary operator
grandfather potential

(primary means not a derivative of another operator)

$$d \geq j_1 + j_2 + 2 - \delta_{j_1,j_2,0} \quad \text{Dim. of the gauge inv. primary operator}$$

$\sigma(x)$ provides the control over UV & IR divergences

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LD & equations of motion

\[ L = L_\varepsilon + L_\sigma - \frac{1}{2} m^2 B^2_\mu + L_{H\sigma}, \quad L_H \rightarrow L_\sigma = -\frac{\sigma}{\sqrt{2}} \sum_{q'} (m_q + x_\sigma y_{q'} y_{q'}) q' \bar{q}' \quad x_\sigma = \frac{m^2_\sigma}{f^2} < 1 \]

\[ L_{H\sigma} = \frac{1}{2} \left[ \left( \partial_\mu H \right)^2 + \left( \partial_\mu \bar{\sigma} \right)^2 \right] - \frac{\lambda}{4} \left( H^2 - \beta^2 \bar{\sigma}^2 \right)^2 - \frac{\eta}{4} \left( \bar{\sigma}^2 - f^2 \right)^2 \quad \beta = \frac{\left< H \right>}{\left< \bar{\sigma} \right>} = \frac{\nu}{f} \]

\[ \partial^2 B_\mu = \frac{1}{\varepsilon} Y_\mu + (1 - \bar{\xi}) \partial_\mu \partial^\nu B_\nu, \quad Y_\mu = g \bar{q} \gamma_\mu q \quad (\ast) \]

\[ B_\mu = \frac{\varepsilon}{m^2} \left[ \partial^2 A_\mu - \frac{1}{\varepsilon} I_\mu - (1 - \bar{\xi}) \partial_\mu \partial^\nu A_\nu \right] \]

Eq. \((\ast)\) + Eq. \(B_\mu(x) = \partial_\mu \bar{\sigma}(x) \Rightarrow \left( \partial^2 \right)^2 \bar{\sigma}(x) \approx 0, \quad f \neq 0 \]

*Dipole eq. for virtual field \(\bar{\sigma}(x)\)*
What is the feature the dilaton field is characterized by?

TPWF (two-point Wightman function) \((!^2)^2'' (x) = 0\) # \((!^2)^2 \bar{\sigma}(x) = 0\)

General solution (expansion),
\[! (x)'' S (\# R^4)\] of temperate generalized functions on \(R^4\)

\[! (x) = b_1 \ln \frac{l^2}{x^2 + i \# x^0} + b_2 \frac{1}{x^2'' i \# x^0} + b_3\]

✓ parameter \(l\) breaks the scale invariance.

(Dilatation properties: \(!'' (x) = ! (x) \# \frac{1}{(8\pi)^2} \ln''\), \('' > 0\))

_allow: est. the propagator of \(! (x)\) ! propagator of DP_
Commutators

\[
\begin{aligned}
\Gamma(x), \Gamma(0) \equiv 2\mathcal{R} \text{ sign}(x^0) \b_1'(x^2) + b_2(x^2)
\end{aligned}
\]

- Coefficients

\[
\begin{aligned}
b_1 ! \quad & CCR \quad \left[ \mathcal{A}(x), \mathcal{A}(0) \right]_{x^0=0} = i \mathcal{g} \quad (3^{(\mathcal{g})}) \\
\end{aligned}
\]

\[
\begin{aligned}
b_2 ! \quad & CCR \quad \left[ \mathcal{\bar{A}}(x), \mathcal{\bar{A}}(0) \right]_{x^0=0} = i (3^{(\mathcal{g})})
\end{aligned}
\]

➢ To fix both \(b_1\) and \(b_2\) we choose:

\[
I = "m^2(\# \sigma \% A)"
\]

(invariant under gauge transformations)

- LD mixing term

\[
!m^2(A " \# \sigma)(B " \# \sigma) \text{ addit. to } \sim !F " B
\]

Stueckelberg-like term

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Propagator of Dark Photon

\[ \Pi^- (p) = p \cdot p^- \Pi(p), \quad \Pi(p) \sim \# \Pi_1(p) + \Pi_2(p), \]

\[ \Pi_1(p) = \frac{1}{\sqrt{1 + \#}} \lim \frac{1}{N^0 \left( p^2 + \lambda^2 + i\# \right)^2} + i' \ 2 \ln \left( l^2 \lambda^2 \right) \Pi_4(p), \]

\[ \Pi_2(p) = \frac{1}{2 \left( \frac{2}{m^2} \right) p^2 + i\#} \]

✓ The strong gauge condition \( B (x) = \Pi^- (x) \) used

○ In case no mixing, \( \Pi^- (p) \# \) standard photon photon propagator

➢ Dilaton mass does not enter the final solution

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Conclusion

1. Influence of Conformal Sector (DP) to SM particle sector;
2. Upper limit for mixing strength \( |<3 \times 10^{-2}| \)

3. Interaction between DP & quarks is mediated by \( \sim \)
4. Dilaton is a portal to DP propagation with \( k^2 (" #B ) = 0 \)
5. DP solutions, DP massive, \( m = 0.83 \, GeV \), \( \sim \) \( = 7.6 \times 10^{-3} \)

6. Dilaton mass does not enter the final solution.
7. If \( \sim = 0 \), \( S \sim \# \# \Rightarrow H \sim \# \#
8. LHC13: decay \( S \sim \) through \textit{a single photon} \( E_T \) signature, with both energies peaked at 0.5ms

\( LHC: \) \textit{channel in scalar decay is the best probe to discover DP}